

ON THE DIRECT NUCLEON DECAY OF HIGH-SPIN SUBBARRIER SINGLE-PARTICLE STATES IN NEAR-MAGIC NUCLEI

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Abstract

The description of the direct nucleon decay of high-spin subbarrier one-particle states in near-magic nuclei is attempted using a simple optical model and the simplest version of the coupled-channel approach. The branching ratios for the direct decay of the several single-neutron states in ^{209}Pb and ^{91}Zr to the ground state and to the low-lying collective states of ^{208}Pb and ^{90}Zr , respectively, are evaluated. Results are compared with recent experimental data.

The one-nucleon transfer reactions are the source of a lot of data on spreading high-lying single-quasiparticle states in medium and heavy nuclei (see e.g. ref. [1] and refs. therein). These data have been successfully described in the case of both near-magic ("hard") [1, 2] and "soft" [3, 4] spherical nuclei. As it seems, the main interest is shifted now to the investigation of decays of the mentioned states. The experimental data on the direct neutron decays of high-spin subbarrier single-neutron states in ^{209}Pb and ^{91}Zr excited by means of the $(\alpha, {}^3He)$ reaction have been reported recently (refs. [5] and [6], respectively).

In the present work we try to describe some of these data: the relative intensities (branching ratios) for the direct neutron decays of the $1k_{17/2}$, $1j_{13/2}$, $2h_{11/2}$ single-neutron states in ^{209}Pb as well as of the $1i_{13/2}$, $1h_{9/2}$, $1j_{15/2}$ single-neutron states in ^{91}Zr to the ground state and to the 3^- and 5^- low-lying excited states of ^{208}Pb and ^{90}Zr . Respectively, a simple optical model (for description of the decay to the ground state) and the simplest version of the coupled-channel approach (for description of the decay to the low-lying collective states) have been used for evaluating the mentioned branching ratios. The results are compared with the data deduced from the experimental cross sections.

In conformity with recent theoretical considerations of the one-nucleon transfer reactions (see e.g. ref. [7]) we start from the reasonable assumption that there exists a vertex descriptive of one-nucleon transfer reaction amplitude. Let $f_{jl}(r, \varepsilon)$ be the radial part of the vertex corresponding to the transferred nucleon having certain values of total (j) and orbital (l) angular momenta. Then the relevant part $\sigma_{jl}(\varepsilon)$ of the energy-averaged inclusive cross section of the one-nucleon transfer to the nucleus in the 0^+ ground state is determined by the strength function corresponding to the vertex f_{jl} , which is supposed to be vanished outside the nucleus:

$$\sigma_{jl}(\varepsilon) \sim -\frac{1}{\pi} \text{Im} \int f_{jl}^*(r, \varepsilon) g_{jl}(r, r'; \varepsilon) f_{jl}(r', \varepsilon) dr dr'. \quad (1)$$

Here, ε is the energy of the transferred nucleon, g_{jl} is the radial part of the energy-averaged single-particle Green function. The simplest description of this Green function can be obtained within the framework of an optical model: $g_{jl} \rightarrow g_{jl}^{opt}$.

To illustrate the resonance-like behavior of the cross section (1) in the vicinity of the energy ε_λ of the subbarrier single-quasistationary state $\lambda \equiv n, j, l$ ($n-1$ is the radial quantum number) we use the pole representation of the optical-model Green functions $g_{jl}^{opt}(r, r'; \varepsilon)$, which is valid within the nucleus (see e.g. ref. [8]). As a result we get:

$$\begin{aligned} \sigma_{jl}(\varepsilon) &\simeq \sigma_\lambda^{(0)} S_\lambda(\varepsilon), \\ S_\lambda(\varepsilon) &= -\frac{1}{\pi} \text{Im} \int g_{jl}^{opt}(r = r'; \varepsilon) dr \simeq \frac{1}{2\pi} \frac{\Gamma_\lambda^\downarrow}{(\varepsilon - \varepsilon_\lambda)^2 + \frac{1}{4}\Gamma_\lambda^{\downarrow 2}}, \end{aligned} \quad (2)$$

where S_λ is the single-particle strength function [3]; $\Gamma_\lambda^\downarrow = 2 \int W(r, \varepsilon_\lambda) |\chi_\lambda^{(0)}(r)|^2 dr$ is the single-particle spreading width, W is the imaginary part of the optical potential; $\sigma_\lambda^{(0)} \sim |\int f_{jl}(r, \varepsilon) \chi_\lambda^{(0)}(r) dr|^2$ is the cross section

of one-particle transfer to the λ state, $\chi_{\lambda}^{(0)}$ is the radial part of the wave function of the single-particle quasistationary state. This wave function is normalized according to the condition $\int |\chi_{\lambda}^{(0)}(r)|^2 dr = 1$. This integral as the previous ones given in this paragraph is taken up to the nucleus radius. From this point onwards we assume that the spreading width is much larger than the escape width for the single-particle direct decay.

The energy-averaged reaction amplitude corresponding to the direct nucleon transfer to a certain single-particle continuum state (the target nucleus remains in the 0^+ ground state) is also determined by the vertex mentioned above. Neglecting the fluctuational part of the energy-averaged cross section, we have:

$$\sigma_{jl,0+}^{dir}(\varepsilon) \sim \left| \int f_{jl}(r, \varepsilon) \chi_{\varepsilon jl}^{(+)}(r) dr \right|^2. \quad (3)$$

Here, $\chi_{\varepsilon jl}^{(+)}$ is the radial part of the energy-averaged single-particle wave function of the nucleon-nucleus scattering problem. This wave function is normalized to the δ -function of energy in the "potential" limit, in which the coupling of the single-particle states to many-particle configurations is neglected. The optical model can be also used for calculating this wave function. The branching ratio for the direct nucleon decay to the 0^+ ground state is defined as the ratio

$$b_{jl,0+}(\varepsilon) = \frac{\sigma_{jl,0+}^{dir}(\varepsilon)}{\sigma_{jl}(\varepsilon)} \quad (4)$$

and can be calculated within the optical model. In the "potential" limit ($W \rightarrow 0$) the branching ratio (4) tends to unity as it follows from eqs.(1),(3).

In the vicinity of ε_{λ} the following approximate representation $\chi_{\varepsilon jl}^{(+)}(r) \simeq A_{\lambda}(\varepsilon) \chi_{\lambda}^{(0)}(r)$ is valid within the nucleus (see e.g. ref. [8]). Using the pole representation for the amplitude $A_{\lambda}(\varepsilon)$ we obtain according to eqs.(1)-(4):

$$b_{jl,0+}(\varepsilon) \simeq \frac{\Gamma_{\lambda}^{\uparrow}(\varepsilon)}{\Gamma_{\lambda}^{\downarrow}}, \quad (4')$$

where $\Gamma_{\lambda}^{\uparrow}(\varepsilon)$ is the single-particle escape width. Eq.(4') illustrates the physical meaning of the branching ratio (4) and shows that this ratio is expected to be nearly independent of the vertex f_{jl} , provided the vicinity of the relevant single-particle resonance is considered. This conclusion is natural, because in view of the absence of the intermediate structure of the single-particle resonance the decays of this resonance are independent of the way of its excitation.

Suppose the target-nucleus excited state can be considered as vibrational with L^{π}, β_L and ω_L being the angular momentum, parity, dynamic deformation parameter and energy of this state, respectively. If the particle-phonon coupling is weak (this condition is fulfilled for near-magic nuclei), the direct part of the energy-averaged cross section corresponding to the nucleon transfer into the single-particle continuum state (the target nucleus remains in the one-phonon state) is described by the formula, which is the direct generalization of eq.(3). The generalization is similar to the transition from the simple optical model to the simplest version of the coupled-channel approach (see e.g. ref. [4]) and leads to the expression:

$$\sigma_{jl,L^{\pi}}^{dir}(\varepsilon) \sim \sum_{j'l'} \left| \int f_{jl}(r, \varepsilon) g_{jl}(r, r'; \varepsilon) v_L(r') \chi_{\varepsilon' j'l'}^{(+)}(r') dr dr' \right|^2 \frac{\langle jl \| Y_L \| j'l' \rangle^2}{2j+1}, \quad (5)$$

where $v_L(r) = (2L+1)^{-1/2} \beta_L R \partial V(r) / \partial r$ is the radial part of the one-phonon transition potential, R is the nuclear radius, V is the single-particle (shell-model) potential, $\varepsilon' = \varepsilon - \omega_L$, $\langle jl \| Y_L \| j'l' \rangle$ is the reduced matrix element. In the "potential" limit eq.(5) can be directly obtained considering the particle-phonon interaction as perturbation. By definition, the ratio of cross sections (5) and (1) is the branching ratio for the direct nucleon decay to the low-lying collective states of the target nucleus:

$$b_{jl,L^{\pi}}(\varepsilon) = \frac{\sigma_{jl,L^{\pi}}^{dir}(\varepsilon)}{\sigma_{jl}(\varepsilon)} \quad (6)$$

In the same approximations used for illustration of branching ratio (4) by means of eq.(4'), the ratio (6) can be expressed in terms of the escape widths $\Gamma_{\lambda,L^{\pi}}^{\uparrow}$ for the direct nucleon decay of the single-particle quasistationary state to the low-lying collective states:

$$b_{jl,L^{\pi}} \simeq \frac{\Gamma_{\lambda,L^{\pi}}^{\uparrow}}{\Gamma_{\lambda}^{\downarrow}} ; \quad \Gamma_{\lambda,L^{\pi}}^{\uparrow} = 2\pi \sum_{j'l'} \left| \int \chi_{\lambda}^{(0)}(r) v_L(r) \chi_{\varepsilon' j'l'}^{(+)}(r) dr \right|^2 \frac{\langle jl \| Y_L \| j'l' \rangle^2}{2j+1}. \quad (6')$$

In accordance with eq.(6') it should be expected that the ratio (6) is also nearly independent of vertex f_{jl} , provided the vicinity of ε_λ is only considered.

In practice branching ratios (4), (6) averaged over finite excitation energy interval Δ are considered (from this point onwards L^π includes 0^+):

$$\langle b_{jl,L^\pi} \rangle_\Delta = \frac{1}{\Delta} \int_{(\Delta)} d\varepsilon b_{jl,L^\pi}(\varepsilon). \quad (7)$$

When Δ contains several single-particle resonances, the averaged branching ratio for the direct nucleon decay from the interval Δ to the L^π state can be defined as follows:

$$\langle b_{L^\pi} \rangle_\Delta = \frac{1}{\Delta} \int_{(\Delta)} d\varepsilon \sum_{jl} w_{jl}(\varepsilon) b_{jl,L^\pi}(\varepsilon), \quad (8)$$

where $w_{jl}(\varepsilon) = \sigma_{jl}(\varepsilon) / \sum_{jl} \sigma_{jl}(\varepsilon)$ is the probability of (jl) -state excitation. These probabilities can be evaluated according to eqs.(2) using the energy dependences of the cross sections $\sigma_\lambda^{(0)}$ and of the strength functions S_λ from the DWBA and optical-model calculations, respectively. Branching ratios (8) can be compared with relevant experimental values (deduced after the elimination of the statistical decay contribution [5, 6]), provided that probabilities w_{jl} are known.

The parameters of the optical-model potential as well as the parameters of the one-phonon states are the input data for evaluating the branching ratios considered. They are the same parameters which are used for the description of the elastic and inelastic nucleon-nucleus scattering by means of the optical model and coupled-channel approach. The choice of the optical-model parameters is performed now within the dispersive optical-model analysis or the variational moment approach (see e.g. refs. [9]). The analysis of experimental data on both the elastic scattering within wide energy interval and the single-particle bound states is needed for the determination of the optical-model parameters. Nevertheless, we use a simplified way for the choice of the optical-model potential as the first step in the analysis of branching ratios (4), (6)-(8). Namely, we use "combined" optical-model potential U_{om} :

$$U_{om}(\vec{r}, \varepsilon) = U(\vec{r}) + \Delta U(r, \varepsilon) , \quad Re \Delta U(r, \varepsilon) = 0.3\varepsilon f_{ws}(r, R, a) , \quad (9)$$

$$-Im \Delta U(r, \varepsilon) \equiv W(r, \varepsilon) = -4a(4.28 + 0.4\varepsilon - 12.8(N - Z)/A) \partial f_{ws} / \partial r .$$

Here, $U(\vec{r}) = V(r) + V_{so}(\vec{r})$ is the shell-model potential of the Woods-Saxon type with parameters taken from ref. [10]:

$$\begin{aligned} V(r) &= -53.3(1 - 0.63(N - Z)/A)f_{ws} , \quad MeV ; \\ V_{so}(\vec{r}) &= 14.02(1 + 2(N - Z)/A)(\vec{\sigma} \cdot \vec{l}) \partial f_{ws} / r \partial r , \quad MeV ; \\ f_{ws}(r, R, a) &= [1 + \exp(r - R)/a]^{-1} , \quad R = 1.24A^{1/3} fm , \quad a = 0.65 fm . \end{aligned} \quad (9')$$

The ability of this potential to reproduce the low-energy part of the experimental single-neutron spectrum for ^{209}Pb and ^{91}Zr is presented in Table 1. The parameters of ΔU in eq.(9), where the neutron energy ε is given in MeV, are taken from ref. [11]. Potential (9),(9') is close to the potential, which has been widely used in ref. [4] for the analysis of the low-energy neutron-nucleus scattering for a great many spherical nuclei.

Using the potential U_{om} in the limit $W \rightarrow 0$ we evaluated the energies ε_λ and the escape widths $\Gamma_\lambda^\uparrow(\varepsilon_\lambda)$ for several single-neutron quasistationary states of ^{209}Pb and ^{91}Zr (the results are given in Table 2). These states give the main contribution to the branching ratios considered. The branching ratios b_{jl,L^π} and $\langle b_{jl,L^\pi} \rangle_\Delta$ have been evaluated according to (1),(3)–(7) for the excitation energy intervals considered in refs. [5, 6]. For these intervals we have evaluated also the branching ratios $\langle b_{L^\pi} \rangle_\Delta$ (8). The results of the DWBA calculations needed for evaluation of the probabilities w_{jl} in eq.(8) have been taken from ref. [12]. The results of the calculations of the mentioned branching ratios, the relevant experimental data [5, 6], the parameters of low-lying states L^π [13] are given in Table 3 and Table 4 for ^{209}Pb and ^{91}Zr , respectively. The method for calculating the optical-model Green functions g_{jl}^{opt} is given e.g. in ref. [4]. The function $\partial f_{ws} / \partial r$ has been used as f_{jl} . The substitution $\partial f_{ws} / \partial r \rightarrow f_{ws}$ changes the $\langle b_{L^\pi} \rangle_\Delta$ value less than 20%. For both nuclei considered the calculated branching ratios $\langle b_{L^\pi} \rangle_\Delta$ are in qualitative agreement with the experimental values for the direct neutron decay to the ground and 3^- states, whereas they are in some disagreement for the direct decay to the 5^- state. The possible reason for the disagreement lies in the description of the 5^- states in terms of the dynamic vibration parameters.

In the present work the method for evaluating the branching ratios for the direct neutron decay of high-spin subbarrier single-particle states in near-magic ("hard") medium and heavy nuclei is given. The method is based

on the use of the optical model and the simplest version of the coupled-channel approach. Some applications of the method have been considered. The next step in development of the method is the use of modern optical-model potentials and of more advanced versions of the coupled-channel approach (see e.g. refs. [9] and [4], respectively). The use of microscopical calculations for the transition potential connected with excitation of the low-lying collective states is also interesting. The method proposed can be also applied to the description of the direct proton decay of subbarrier single-proton states. Relevant experimental data are soon expected [5].

The interesting and not fully solved theoretical problem is the description of the direct nucleon decay of subbarrier single-particle states in "soft" spherical nuclei where the strong particle- 2^+ -phonon coupling takes place. The methods for consideration of this coupling [3, 4] can be applied to the description of the direct nucleon decay to the ground state and should be apparently improved for the description of the direct nucleon decay to the first 2^+ -state. An attempt of consideration of this problem has been undertaken in ref. [14]. Thus, a comparison of the calculated branching ratios with experimental ones can be a serious test of the theory of the strong particle- 2^+ -phonon coupling. For this reason, the accumulation of relevant experimental data seems also to be necessary.

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Table 1

Calculated and experimental [15] energies for several single-neutron bound states of ^{209}Pb and ^{91}Zr .

nucleus	^{209}Pb				^{91}Zr				
λ	$2g_{9/2}$	$1i_{11/2}$	$1j_{15/2}$	$2g_{7/2}$	$2d_{5/2}$	$3s_{1/2}$	$2d_{3/2}$	$1h_{11/2}$	$1g_{7/2}$
$\varepsilon_{\lambda}^{calc}, (-1) MeV$	4.27	2.53	3.03	0.18	6.79	4.96	3.89	2.73	4.77
$\varepsilon_{\lambda}^{exp}, (-1) MeV$	3.94	3.16	2.52	1.45	7.19	5.99	5.16	5.03	5.00

Table 2

Calculated energies and escape widths for several single-neutron quasistationary states of ^{209}Pb and ^{91}Zr .

nucleus	^{209}Pb			^{91}Zr		
λ	$2h_{11/2}$	$1k_{17/2}$	$1j_{13/2}$	$1i_{13/2}$	$1h_{9/2}$	$1j_{15/2}$
$\varepsilon_{\lambda}, MeV$	2.680	4.989	8.056	7.319	7.349	17.320
$\Gamma_{\lambda}^{\uparrow}(\varepsilon_{\lambda}), keV$	105	2.1	160	185	660	3180

Table 3

Calculated and experimental branching ratios for the direct neutron decay of ^{209}Pb from the excitation energy intervals $\Delta_1=8.5-10$ MeV and $\Delta_2=10-12$ MeV (upper and lower lines, respectively).

L^{π}	ω_L MeV	β_L	$\langle b_{jl,L^{\pi}} \rangle_{\Delta}, \%$			$\langle b_{L^{\pi}} \rangle_{\Delta}, \%$	
			$2h_{11/2}$	$1k_{17/2}$	$1j_{13/2}$	calc	exp
0^+	0	0	27	0.07	0.57	0.41	0.49
			35	0.35	1.9	0.81	0.36
3^-	2.6	0.1	1.10	0.98	0.69	0.92	2.1
			0.81	1.30	0.76	1.13	1.5
5^-	3.2	0.05	0.46	0.11	0.38	0.16	7.0
			0.30	0.25	0.31	0.27	1.3

Table 4

Calculated and experimental branching ratios for the direct neutron decay of ^{91}Zr from the excitation energy interval $\Delta=11-15$ MeV.

L^{π}	ω_L MeV	β_L	$\langle b_{jl,L^{\pi}} \rangle_{\Delta}, \%$			$\langle b_{L^{\pi}} \rangle_{\Delta}, \%$	
			$1i_{13/2}$	$1h_{9/2}$	$1j_{15/2}$	calc	exp
0^+	0	0	1.1	4.5	0.2	1.6	1.4
5^-	2.31	0.08	0.5	0.2	0.1	0.4	0.
3^-	2.75	0.2	3.1	0.9	0.1	2.1	2.4